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AXIAL MODE COMBUSTION INSTABILITY IN SOLID PROPELLANT ROCKET MOTORS

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by

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Research Department

ABSTRACT. A comparison was made of the combustion instability characteristics of several commercial composite propellants. Tests were made at 300 cps in the pressure range 300-1,500 psi, using a center-vented burner configuration to minimize acoustic losses in axial acoustic modes. In addition, tests were made on the effect of aluminum particle size of a polyurethane-ammonium perchlorate-aluminum propellant.

All propellants tested were found to be unstable in the low-loss burner. At low pressures, instability was spontaneous with all of the commercial propellants, while two of these propellants were stable at high pressure unless a pressure pulse was introduced by a small powder charge. Two forms of instability were observed, one manifested by sustained, mild, sinusoidal pressure oscillations in the first axial mode of the burner. The other form was manifested by very severe first-mode oscillations with major increases in mean burning rate.

Changes in aluminum particle size led to a complicated array of instability behavior as a function of particle size and pressure.

U.S. NAVAL ORDNANCE TEST STATION

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FOREWORD

The work summarized in this report was carried out under Advanced Research Projects Agency Work Orders No. 22-61, Contract RMMP-7A 073/216-7/F009-06-001, and No. 22-62, Contract RMMP-7a 050/216-1/F009-06-01, with the goal of obtaining a comparison of the intermediate frequency oscillatory combustion behavior of current commercial solid propellants. This constitutes the final report on this work assignment.

Concurrently, testing was carried out under Bureau of Naval Weapons Special Projects Task Assignment Sp 19422 to study this type of instability in greater detail. For completeness, results under this second project related to the effect of aluminum particle size have been included in the present report. Additional work on this project is continuing under Task Assignment RMMP-22-095/216-1/F009-06-04.

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INTRODUCTION

Prior to 1958, experience with combustion instability in solid propellant rocket motors was confined primarily to oscillatory behavior in the transverse modes of the combustion chamber (Ref. 1). The frequency of this oscillatory behavior was ordinarily above 1,000 cps. It had been observed that addition of aluminum and other metals and metal oxides to the propellant in concentrations of a few percent ordinarily led to suppression of this type of combustion instability. Because of the widespread adoption of powdered aluminum as a fuel in solid propellants in the period following 1958, this type of combustion instability has not been a serious problem in most recent missile programs (Ref. 2). Lacking knowledge regarding the mechanism by which aluminum suppressed high frequency combustion instability, there remained the anxiety that suppression would not be equally effective at the lower frequencies which would be characteristic of larger rocket motors under development (Ref. 3). Subsequent experience in development programs has shown that aluminum is indeed a very poor suppressant for combustion instability in the frequency regime 100-1,000 cps, characteristic of the axial modes of larger rocket motors developed subsequent to 1958. Instability in these modes has been encountered in several development programs including SUBROC, Improved Tartar, Genie, Sidewinder 1-C, 23 KS 20,000, Bullpup, Iroquois, and others (Ref. 2).

The instability behavior observed in the aforementioned development programs exhibited many characteristics that were in sharp contrast to earlier experiences with high frequency combustion instability. In general, the correlation between susceptibility to instability and the composition of the propellant or its ballistic characteristics was very different than with high frequency instability. Further, it was observed that the instability might occur either as a sustained low-amplitude oscillation of sinusoidal wave form (Improved Tartar), or as an extremely severe oscillation at about the same frequency but with a highly nonsinusoidal wave form (Improved Tartar, SUBROC, etc.) with spontaneous transitions from the first to the second of these forms being occasionally observed. In addition, it was observed that the severe form of instability might be initiated on some occasions by a finite pressure disturbance in the motor under conditions which would not otherwise lead to unstable behavior (Ref. 4). Once the severe form of instability was started it usually continued for the duration of the burning period and was usually accompanied by a substantial increase in equilibrium pressure in the motor. The presence of high concentrations of powdered aluminum fuel in the propellant was no guarantee against

such unstable behavior, and it was found that substantial changes in the nature of the instability could be produced by changes in the particle size of the powdered aluminum (Ref. 2, 4 and 5). Because of the wide variety of shapes and sizes of the rocket motors from which the available information on this type of instability was collected, it was impossible to arrive at any reliable systematic trends which would be applicable to future propellant and motor development work. Accordingly, it was considered desirable to carry out a screening program for the purpose of comparing the general character of the axial mode combustion instability characteristics of various commercial solid propellants, using a single motor configuration designed specifically for this purpose. Previous experience at the Naval Ordnance Test Station (NOTS) with a special center-vented burner configuration, often used in laboratory-scale investigations of unstable combustion, had indicated that this configuration would be ideal for the screening program. Because this burner configuration is somewhat more unstable than most rocket motor configurations, there was reason to believe that propellants currently in successful use in development programs would exhibit some measure of instability in this burner. Further, it had been observed that this burner could be used for the purpose of comparing propellants over a wide range of pressures and burning rates without introducing undue contribution of nozzle throat area to the experimental results as would be the case in a conventional end-vented rocket motor.

In August of 1961, the Advanced Research Projects Agency (ARPA) provided initial support for the preparation of test burners and the testing of propellants in a screening program for ten commercial propellants, under ARPA Work Order 22-61. Preliminary tests were undertaken on improvised burner hardware to verify the suitability of the chosen center-vented burner configuration, and negotiations were initiated to obtain the commercial propellants. A Sidewinder 1-C motor was modified to a center-vented configuration and was tested with Goodrich E-107 propellant. Axial-mode oscillations started early in each test firing and continued at large amplitudes throughout the burn. On the basis of these test results, a final design of the burner was made and eight burner chambers were manufactured. In addition, negotiations were started for construction of loading fixtures and loading of propellants by Aerojet-General Corporation, Hercules Powder Company, and Thiokol Chemical Corporation. Under the original budget it was anticipated that loading hardware would be funded out of the original allocation for this program and that the actual propellant loading operations would be carried out at no cost to the government by the companies involved. Further negotiation revealed that certain of the propellants could not be obtained without specific funding for the loading operations, and a second increment of funding was provided by ARPA for this purpose under amendment to ARPA Work Order 22-61. The propellants originally selected for this program are shown in Table 1 with their nominal compositions. Of the propellants in Table 1, the following were provided to the government at no cost: TPG-3133, TPH-3062,

TABLE 1. Comparison of Propellant Ingredients

		Propellant type / Agency / Application	E-107-1 NOTS Research	E-107-2 NOTS Research	E-107-3 NOTS Research	TPG-3133 Thiokol SUBROC	TPG-3013A Thiokol SUBROC	ANP-2915JU Aerojet Improved Tartar	ANP-3027CH Aerojet Improved Tartar	TPH-3062 Thiokol Surveyor	ANP-2969KH Aerojet Polaris	ANP-2874HO Aerojet Improved Tartar	EJC Hercules Polaris	DDP-70 Hercules Polaris
Oxidizer	Ammonium Perch.	Total weight, %	57.3	57.3	57.3	62.8	65.0	72.0	67.0	70.0	55.0	61.0	5.0	20.9
		Average particle size, μ	200	200	200	15/180	15/180	6/100/180	6/100	15/180/400	13/100/180	13/180	100% < 25μ	100% < 150μ
		Weight distribution, %	.....	.....	.....	74/26	77/23	20/70/10	20/80	71/24/5	10/60/30	13/87	.....	.....
		Remarks	.....	.....	.....	Bimodal	Bimodal	Trimodal	Bimodal	Trimodal	Trimodal	Bimodal	.....	.....
	Other	Type	.....	.....	.....	.....	.....	.....	.....	.....	.....	Nitroguanidine	HMX	.....
		Weight, %	.....	.....	.....	.....	.....	.....	.....	.....	.....	21	25.8	.....
		Particle size, μ	.....	.....	.....	.....	.....	.....	.....	.....	.....	60	18	.....
NG		Nitroglycerine, Wt. %	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	32.6	25.3
Fuel	Aluminum	Total weight, %	17.7	17.7	17.7	14.5	13.0	13.0	17.0	16.0	20.0	.....	18.0	21.6
		Av. particle size, μ	7	21	41	9.5/32	32	50	32	30	8	.....	32	32
		Wt. distribution, %	.....	.....	.....	69/31	.....	.....	.....	.....	.....	.....	.....	.....
		Remarks	Narrow cut, spherical	Narrow cut, spherical	Narrow cut, spherical	Bimodal	.....	.....	.....	Spherical	.....	.....	.....	.....
	Binder	Type	Polyurethane	Polyurethane	Polyurethane	Polyurethane	Polyurethane	Polyurethane	Polyurethane	Polyurethane	Carboxy terminated polybutadiene	Polyurethane	Nitrocellulose	Nitrocellulose
		Weight, %	25.0	25.0	25.0	22.7	22.0	15.0	16.0	14.0	25.0	18.0	18.6	32.2
Ballistics		Flame temp., °R	5330	5330	5330	4890	5020	6120	6160	6160	6440	4160	6968	6688
		I_{sp}, lbs-sec/lbm[a]	256/236	256/236	256/236	249/235	250/235	260/247	263/245	264/246	264/243	225/218	270/255	262/244
		Burning rate pressure exponent, n	0.14	0.51	0.37	0.21	0.21	0.21-0.27[b]	0.12-0.41[c]	0.29	0.32	0.11	0.51	0.57
		Burning rate, in/sec, at 500 psi / 1,000 psi	0.162 / 0.180	0.102 / 0.129	0.096 / 0.125	0.130 / 0.150	0.120 / 0.140	0.330 / 0.380	0.330 / 0.360	0.240 / 0.290	0.250 / 0.280	0.075 / 0.082	0.450 / 0.620	0.470 / 0.590

[a] Theoretical and experimental values given.
[b] Higher exponent above 1,500 psia.
[c] Higher exponent above 2,200 psia.

ANP-2915JU, ANP-2874HO, and ANP-2969KH. The following propellants were provided by purchase from the second increment of ARPA funding, including some loadings made at NOTS: E-107, ANP-3027CH, TPG-3013A. A contract for preparation of loading hardware for EJC and DDP-70 propellants was executed, but delays in contract negotiations prevented loadings before expiration of funds available for loading operations. Efforts are continuing to accomplish loading and testing under subsequent funding.

Completion of this program involved development and evaluation of a suitable test burner; development of suitable instrumentation; procurement of 42 propellant charges and mixing and casting of 50 more at NOTS; finishing and loading propellant charges at NOTS; conduct of the test operations themselves at NOTS; reduction and interpretation of test records; and completion of the present final report. The last propellant charge blanks were supplied by the contractors on 28 May 1964. The present report summarizes all the results of the test program.

DESCRIPTION OF EXPERIMENTAL SETUP AND INSTRUMENTATION

The propellant charge configuration chosen for this work is an internal-burning, circular cylindrical charge inhibited on the ends and the outside surface (Fig. 1). The propellant charge is cast in a micarta sleeve 5 7/17 inches in outside diameter and 75 3/4 inches long with a 7/32-inch wall thickness. This cartridge-loaded arrangement was selected in preference to a case-bonded charge in order to minimize the number of test burners required in the program. Micarta sleeves and loading hardware were provided for each contractor, who could thus proceed with loading operations independently of the others and independently of the status of the test motors. The circular perforation in the charge was chosen to minimize the complexity of fabrication and inspection, and to provide a reasonably simple acoustical configuration for purposes of interpretation of results. A relatively thin charge web was chosen in order to minimize burning time and correspondingly minimize the deterioration of motor components during burning, and in order to minimize the total burning surface area change during burning. The thin web posed a mild problem insofar as obtaining high quality, void-free loadings, but X-rays of completed propellant charges showed that loading operations had been carried out effectively by the suppliers. The charge blanks provided by the suppliers were machined on the ends at NOTS to a final length of 69 1/2 inches with a small chamfer at the interface between the propellant and the sleeve. The end surface was then inhibited by silica-filled epoxy potting compound (Fig. 1), which coated the entire end and filled the chamber at the charge-sleeve interface to obtain maximum protection against interface burning in the

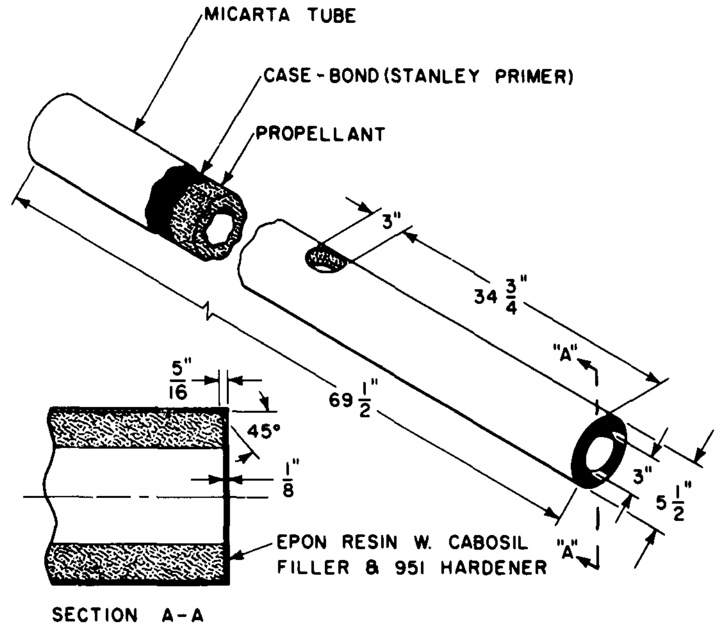


FIG. 1. Solid Propellant Charge, Showing Micarta Sleeve, Epoxy End Inhibiting, and Radial Vent Hole.

event of bonding failure between propellant and sleeve. In addition, a three-inch-diameter perforation was drilled radially, midway between the ends of the propellant charge to accommodate for exhaust of propellant gases to the center vent of the burner.

DETAILS OF THE BURNER

The final burner configuration is shown in Fig. 2. Eight of these burners were constructed. The burner tube was 72 inches long, 6 1/2 inches in outside diameter, and 5 9/16 inches in inside diameter. The nozzle assembly was connected to the burner tube by a massive block which was welded to the motor wall midway between the ends of the burner. The nozzle inserts were made of graphite and were replaceable to provide for the different nozzle sizes that were required in the program. Upstream of the nozzle throat, a contoured entry sleeve of graphite was also used to protect the metal components from erosion and permit repeated use of the burner tubes for a long series of tests. The end assemblies were held on by a threaded retainer ring which mated to threads on the outside of the motor tube. On one end the closure plate was equipped with fittings for two types of pressure transducers, a Photocon high frequency response transducer and a Wiancko intermediate frequency response transducer. The other endplate was equipped with a shear-ring arrangement which permitted the plate to be ejected in the

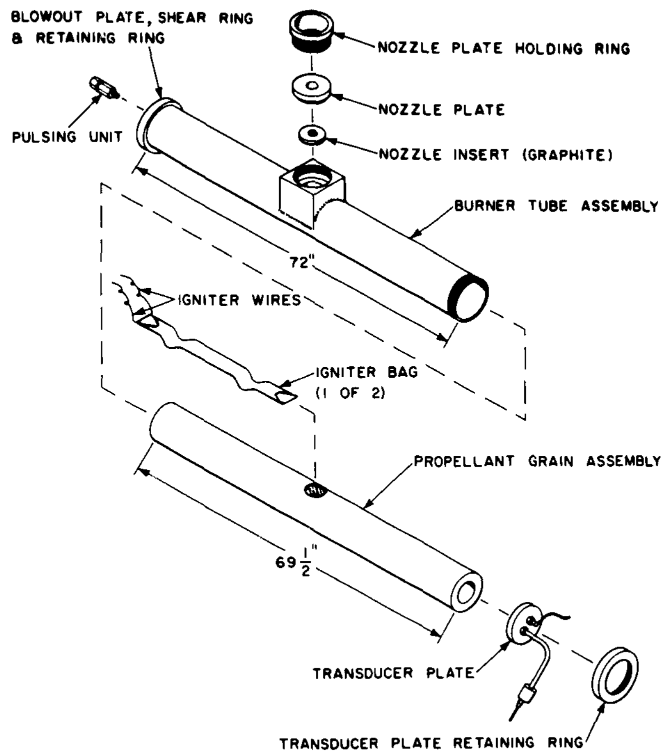


FIG. 2. Center-Vented Burner.

event of dangerously high burner pressures. This endplate was also equipped with a small tubular "pulsing" unit, containing a black powder charge and a shear disc, which could be fired during a test by means of an electrical initiator, thereby permitting the generation of a substantial pressure wave in the motor at the desired time during the test. The pulsing unit was similar to that developed at the Canadian Armament Research and Development Establishment (CARDE) for the same purpose and was based on drawings supplied by that organization (Ref. 6).

LOADING AND FIRING PROCEDURE

Loading of the burners was ordinarily carried out at least 24 hours before scheduled firing time. Propellant charges were inserted in the tubes with the vent hole aligned with the nozzle. In order to avoid undesirable and nonreproducible acoustic effects produced by the interspace between the propellant cartridge and the motor tube, the space was filled with a 90-weight lubricating type grease. The filling operation was accomplished by use of Zerk fittings placed at seven locations on each burner tube (three equally spaced at each end of the tube and one placed at the center opposite the nozzle block). Grease was

injected with a conventional grease gun until it had flowed into the interface and begun to emerge out around the vent hole at the midpoint of the charge. Flow of the grease out around the ends of the charge was prevented by the use of a rubber diaphragm pressed on the end of the charge during "greasing." The diaphragm was removed before final endplate assembly. Following this loading operation, the motor was placed in a temperature conditioning box for a minimum of 24 hours before firing. When ready to fire, the motor was removed from the temperature conditioning box and fastened on the test stand. At that time the igniter was inserted, the instrumented endplates assembled to the motor tube, and the firing circuits connected to the igniter and the pulsing unit. These operations ordinarily required less than 15 minutes, and during this time the temperature change in the inside of the motor was monitored by a thermometer inserted through the nozzle. On those occasions in which the environmental temperature was significantly different than 70°, the motor was covered with a blanket to minimize heat transfer; if the thermometer in the nozzle indicated a temperature change of more than 5°F, the motor was replaced in the temperature conditioning box and fired at a later time.

INSTRUMENTATION

The instrumentation arrangement used during this program was chosen primarily for obtaining accurate records of oscillatory behavior. Utilization of techniques and equipment successfully applied in previous unstable combustion work at NOTS provided test data which would permit chamber pressure measurements to be made of the following: frequency of oscillations, amplitude of oscillations, rates of change of oscillation amplitude, and effect of oscillatory combustion on the mean chamber pressure (Ref. 7).

The specialized instrumentation required for this program was not routinely operational at the active test sites suitable for firing of 50-lb charges. Since the delivery of propellant charges was expected to extend over several months, testing operations would be intermittent. At active test sites this entailed repeated setup of special instrumentation, with associated high cost and unreliability. An alternate choice was made to assemble the instrumentation in a portable console and conduct tests at an otherwise dormant test site. This facility was manned by three men during the present tests and remained unused but ready between periods of testing.

The instrumentation used for the tests reported here is shown in Fig. 3. Little description is needed of the details as the pertinent information is included in the block diagram of instrumentation (Fig. 4). It should be noted, however, that the use of two pressure transducing systems, high-pass and low-pass filtering, amplification on several channels, and the use of three recording systems was arranged to provide

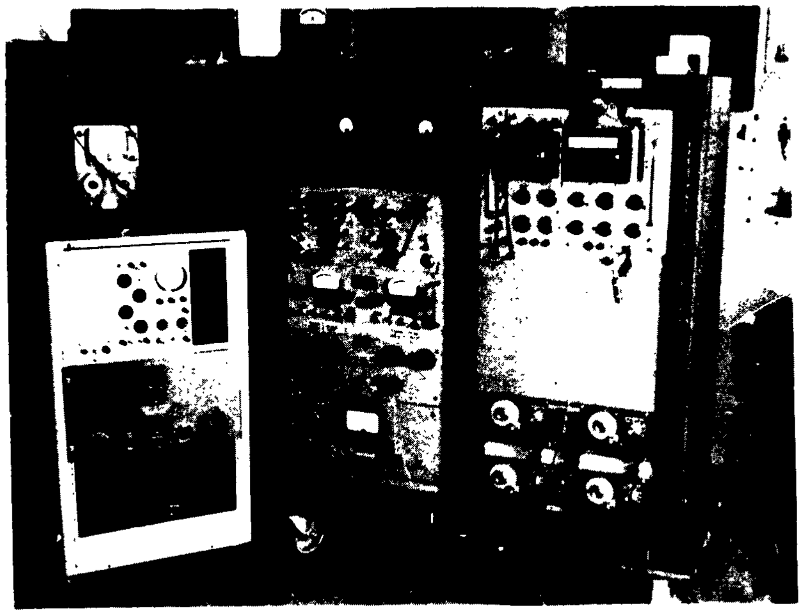


FIG. 3. Instrumentation Console.

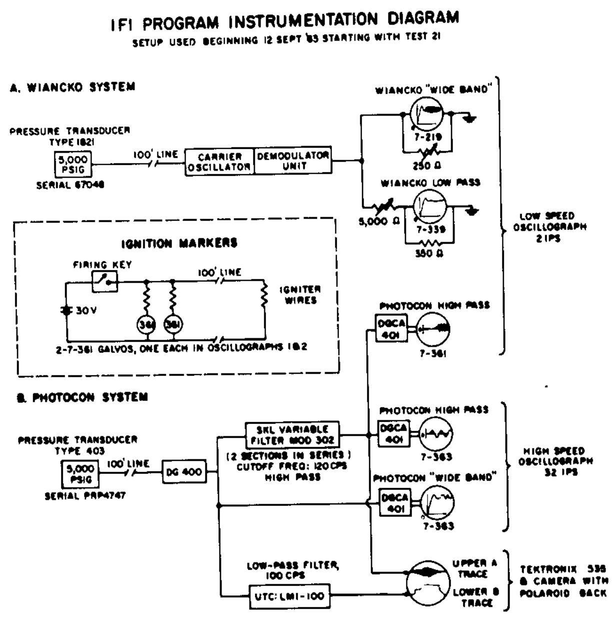


FIG. 4. Block Diagram of Instrumentation.

a redundancy which would minimize loss of data in the event of failure of any one component in the system. In addition, the arrangement allows cross-channel comparisons to be made in cases where the amplification factor (or sensitivity) of any one channel might be questioned.

All data were recorded on photosensitive paper. Recording speeds varied from 32 inches per second (ips) on the high-speed oscillograph to as low as 0.15 ips on the cathode ray oscilloscope. Diagrams depicting the type of information recorded on each channel are presented in Fig. 5. A brief verbal description is presented below.

Figure 5a represents the data recorded on the high-speed oscillograph (32 ips). Both traces on this record are derived from the Photocon pressure-measuring system as used in this test work; the channel had a flat frequency response in excess of 1,500 cps. The oscillograph used to record this data was a Consolidated Electrodynamics (CEC) Model 5-116.

1. The upper trace is high-pass filtered and amplified to provide a sensitivity of 200 psi/inch. This channel resolves oscillations under 10 psi peak-to-peak and thus allows investigation of mild oscillatory behavior. Wave form indicated in this channel is unreliable because of phase distortion.

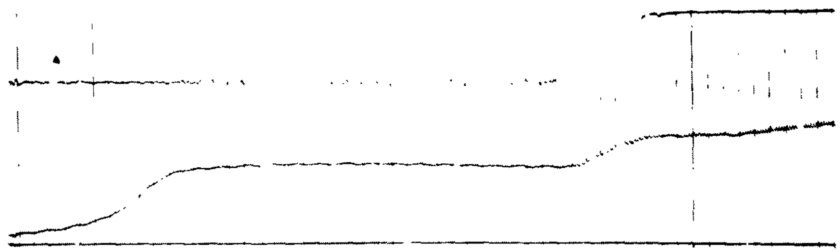
2. The lower trace is amplified but not filtered and is recorded with a sensitivity of about 1,600 psi/inch. This is a "wide-band" channel and contains data representing all frequencies from DC to the maximum of the system (1,500 cps). This channel allows correlation between mean chamber pressure changes and change in oscillatory behavior. Severe oscillations can be examined on this channel because of its lower sensitivity. The degree to which phase distortion might alter interpretation of details of complex wave forms was not evaluated for either of the two channels on this oscillograph, but the wave form of the lower trace is thought to be fairly accurate.

Figure 5b represents data from the low-speed oscillograph, a CEC Model 5-116 recording at 2 ips, and contains three channels of information which are:

1. High-pass filtered and amplified Photocon signal (uppermost trace) of 560 psi/inch sensitivity which records the oscillation amplitude and is unaffected by mean chamber pressure variations. This channel is a compressed time equivalent of the upper trace on the high-speed oscillograph.

2. Low-pass Wiancko signal which records the mean chamber pressure; channel sensitivity is 1,000 psi/inch.

3. "Wide-band" Wiancko signal which contains information from DC to the maximum frequency of the system. This channel is a Wiancko-



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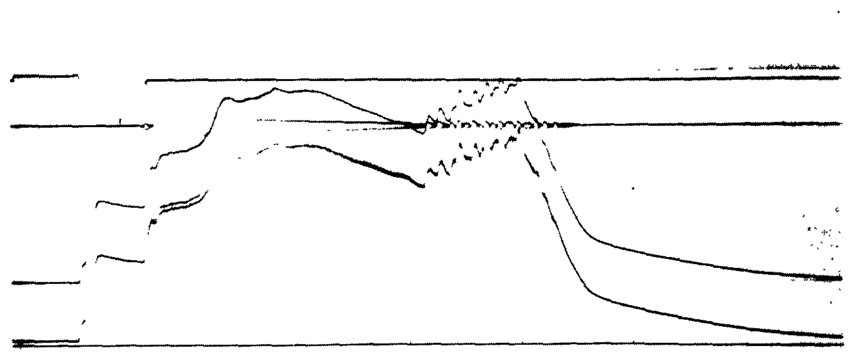
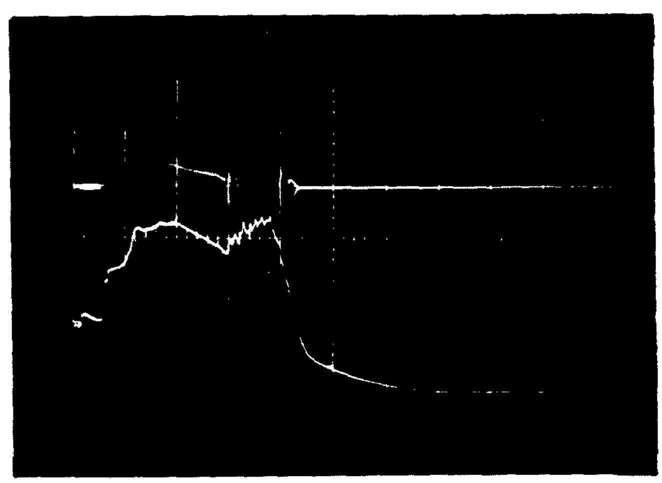


b



c

FIG. 5. Test Records on Various Recording Channels.

derived, compressed-time version of the lower trace on the high-speed oscillograph, but derived from a Wiancko transducer; channel sensitivity is 1,000 psi/inch, and frequency response is estimated to be linear to 350 cps.

Figure 5c represents data recorded by the cathode ray oscilloscope. The recording speed was varied from 0.66 ips to 0.15 ips to suit test conditions. Most tests, however, were run with a sweep rate of 0.33 ips. Data were recorded on Polaroid film which proved to be extremely convenient because it provided a record of the firing little more than ten seconds after the firing of each burner. Decisions as to changes in nozzle diameter and igniter size could be made on the spot; there was no waiting required for oscillograph data processing.

Periodic calibration of the instrument system was accomplished through a two-part procedure:

1. All DC coupled channel sensitivities were determined by applying known static pressure from a conventional dead-weight tester.

2. AC channel sensitivities were determined by applying a 300-cps sine-wave voltage to the system. The peak-to-peak voltage was set to a value equivalent to 100 psi peak-to-peak which was determined by static calibration information from the cathode ray oscilloscope.

TYPICAL TEST DATA

Before turning to a general summary of the test program and the test results, it seems advantageous to point out at this point the different types of behavior that were observed during the test program, including the way in which these observations were made with the particular pressure traces that have been described in the foregoing. Two classes of oscillatory behavior occurred in this test program which are referred to here as mild form and severe form of instability. The mild form, shown in Fig. 6, initiated typically early during the test in a spontaneous manner, grew to a small amplitude with a sinusoidal wave form and continued throughout the test (usually with slowly decreasing amplitude) unless interrupted by severe form instability. The severe form of instability initiated spontaneously in approximately 80% of the tests. It was usually preceded by a sharpening of the wave form of the mild instability, followed by a rapid growth in amplitude to a value typically ten times that of the mild form of instability (Fig. 7). In most tests the transition from mild form to severe form of instability occurred very early in burning, but in some instances this would be delayed for one or two seconds. At low mean pressures the transition from mild form to severe form was less easy to identify, and frequently involved a gradually growing amplitude for a substantial portion of the

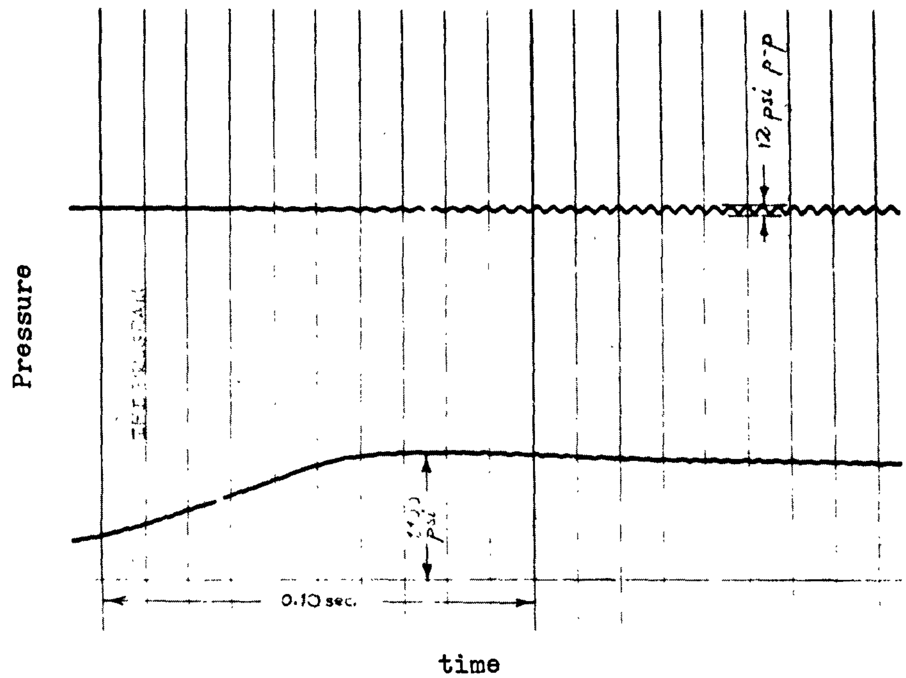


FIG. 6. Test Record of Mild Form Instability

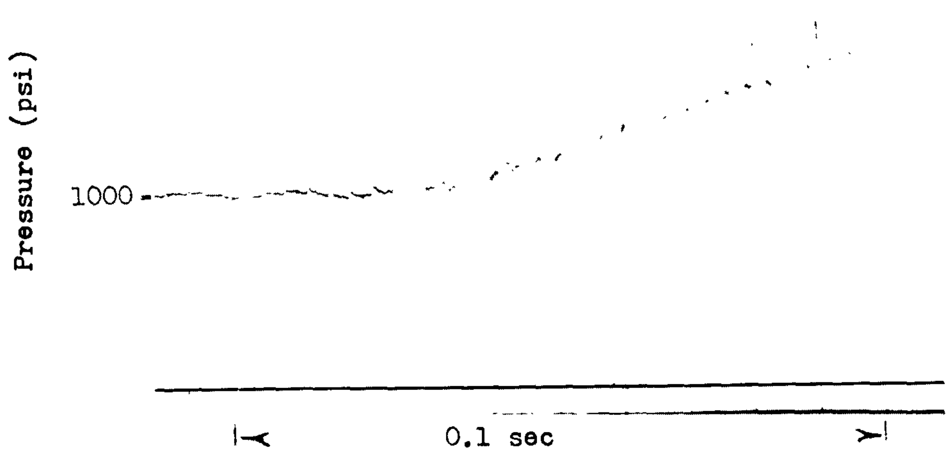


FIG. 7. Test Record Showing Spontaneous Transition From Mild to Severe Form Instability.

burning period. Certain of the propellants would not exhibit severe form instability spontaneously, but in all but one instance this form of instability could be induced by use of the pulsing system described previously (Fig. 8). The prevalence of mild form instability could not be fully assessed, because the rapid development of severe form in some tests precluded distinguishment of two separate forms. However, the mild form instability seemed to be present in advance of the severe form in most tests manifesting severe form, including the tests where severe form occurred only after pulsing. Of the tests which did not show severe form instability without pulsing, all showed mild form instability except the E-107-3 coarse aluminum test at low pressure. The presence of the mild form of instability in tests without severe form suggests that there are two substantially independent mechanisms involved. The mild form of instability was evidently less sensitive to the test variables than the severe form. A complete summary of tests conducted is presented in Table 2, and a summary of pressure-time curves obtained is shown in Fig. 9.

PROPELLANTS

The original selection of propellants for this program was described in Ref. 8 and was based on the philosophy that a broad representation of currently available commercial propellants would be tested, including some propellants which had been involved in combustion instability problems in development programs. Because it was not known in advance what ingredients or ballistic variables were most important to the occurrence of this type of combustion instability, considerable detail was requested from the suppliers regarding the ingredients and composition of the propellant and ballistic data. In addition, samples of the propellant were obtained not only for the center-vented burner tests, but also for end-burner tests and window-bomb tests. Samples of the ammonium perchlorate and the aluminum powder used in each propellant were requested in order that subsequent studies of particle size distribution and shape could be made if it appeared merited. Assessment of the role of the different ingredients in the instability behavior does not yet seem feasible. However, a qualitative description of propellant variables and history is summarized in the following for future use and interpretation.[1]

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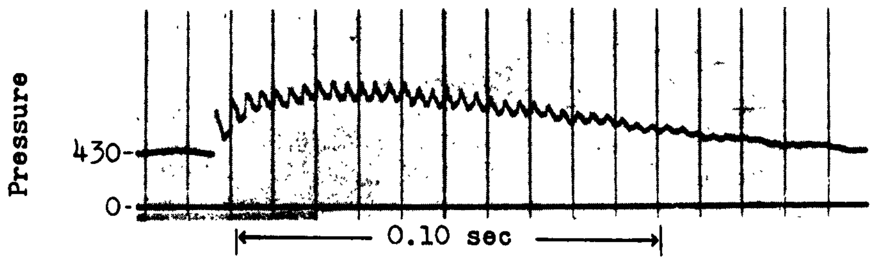
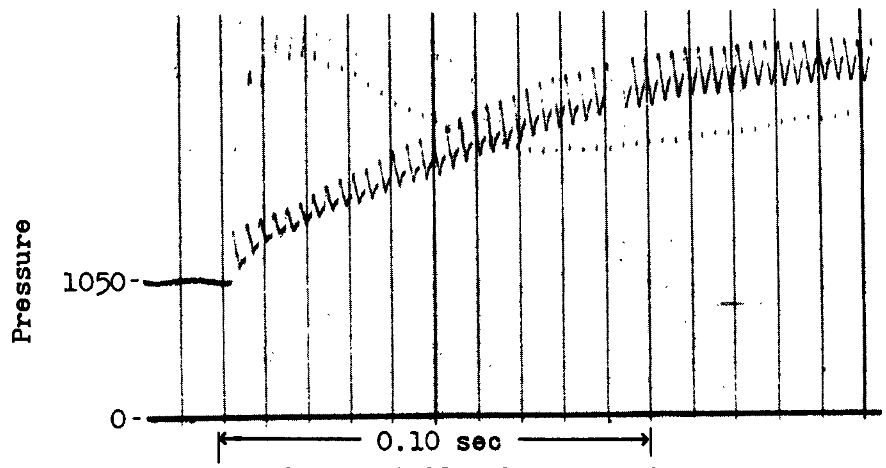
[1]Laboratory studies of the propellants and ingredients are being made on a subsequent program funded by the Bureau of Naval Weapons.



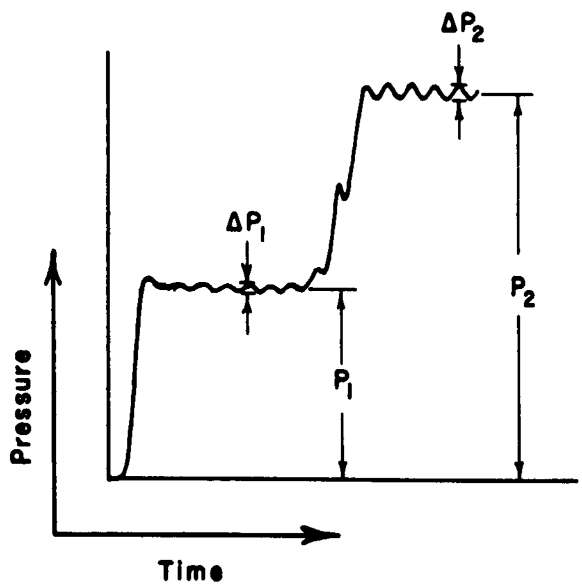
a. Stable when pulsed.



b. Unstable when pulsed.

FIG. 8. Test Records Showing Pulsed Operation.

ILLUSTRATION AND EXPLANATION OF TERMS USED IN TABLE 2:



K_n Ratio of propellant burning surface area to nozzle throat area

P_c Equilibrium chamber pressure

Severity of oscillations:

Mild form $\Delta P_1/P_1$

Severe form $\Delta P_2/P_2$

Pressure rise ratio: P_2/P_1

TABLE 2. Summary of Firings Conducted

Propellant type	Test no.	Initial value K_n	Initial value P_c psig	Mild form Severity	Mild form Duration	Severe form Severity	Severe form Pressure rise ratio	Severe form Initiation
E-107-1	31	290	470	0.02-0.16	To pulse	0.390	1.55	Pulsed
	30	290	480	0.062	To end	No oscil.	----	None
	29	738	1,180	0.009	To end	No oscil.	----	None
	35	738	1,260	0.008	To pulse	0.055	1.59	Pulsed
E-107-2	32	220	250	0.03-0.08	To end	No oscil.	----	None
	33	340	450	0.022	2.80	0.100	1.12	Spont.
	24	340	500	0.100	0.80	0.178	1.14	Spont.
	23	738	1,000	No data	0.72	0.143	1.40	Spont.
	34	738	1,030	0.014	0.95	0.063	1.45	Spont.
	37	1,030	1,400	0.007	0.60	0.071	1.72	Spont.
	25	1,030	1,500	0.013	0.38	0.030	2.06	Spont.
E-107-3	40	340	420	0.000	To pulse	Stable	----	Pulsed
	41	738	800	0.013	To pulse	0.097	2.95	Pulsed
	26	738	1,000	0.010	To end	No oscil.	----	None
	27	1,030	1,200	0.004	To end	No oscil.	----	None
	28	1,030	1,200	0.004	To pulse	0.044	2.65	Pulsed
TPG-3133	70	266	260	0.155	0.13	0.690	2.00	Spont.
	63	450	620	0.060	To pulse	0.091	1.25	Pulsed
	76	650	850	0.030	To pulse	0.125	1.93	Pulsed
	58	680	1,000	0.010	To pulse	0.070	1.50	Pulsed
	42	1,500	3,250	0.000	To pulse	No data	----	Pulsed
TPG-3013-A	69	226	260	0.00-0.066	0.10	1.090	1.84	Spont.
	60	400	450	0.00-0.067	0.10	0.830	2.40	Spont.
	57	600	700	0.029	1.20	0.390	3.15	Spont.
	38	600	850	0.023	To end	No oscil.	----	None
	75	685	950	0.021	3.30	0.210	2.80	Spont.
	39	890	1,400	0.007	To pulse	0.043	2.16	Pulsed
ANP-2915JU	78	100	350	0.00-0.057	1.00	0.750	1.50	Spont.
	65	160	400	0.00-0.035	0.40	0.750	1.29	Spont.
	62	275	1,100	0.00-0.020	0.08	0.560	1.52	Spont.
	73	280	1,150	0.00-0.025	0.06	0.580	1.46	Spont.
	55	375	1,200	0.00-0.025	0.09	0.470	2.00	Spont.
ANP-3027CH	77	100	450	0.00-0.110	1.00	0.182	1.00	Spont.
	66	162	600	0.00-0.030	0.07	0.219	1.05	Spont.
	61	300	1,150	0.00-0.035	0.04	0.164	1.13	Spont.
	72	300	1,170	0.00-0.009	0.03	0.120	1.00	Spont.
	53	420	1,800	----------[a]	----[a]	0.136	1.15	Spont.
TPH-3062	59	115	180	0.033	0.70	1.430	1.75	Spont.
	52	209	500	0.00-0.060	0.07	0 875	1.60	Spont.
	64	209	500	0.00-0.120	0.07	0.875	1.45	Spont.
	71	350	1,600	----------[a]	----	0.428	1.25	Spont.
ANP-2969KH	67	158	460	0.100	To pulse	0.120	1.10	Pulsed
	51	310	1,100	0.027	0.15	0.270	1.09	Spont.
	74	360	1,320	0.022	0.07	0.250	1.08	Spont.
ANP-2874HO	56	200	80	0.00-0.20	0.60	1.650	2.00	Spont.
	68	250	200	0.00-0.05	0.50	0.940	2.30	Spont.
	54	660	330	---------[a]	----	0.630	6.40	Spont.

[a] Rapid growth to severe form on ignition peak.

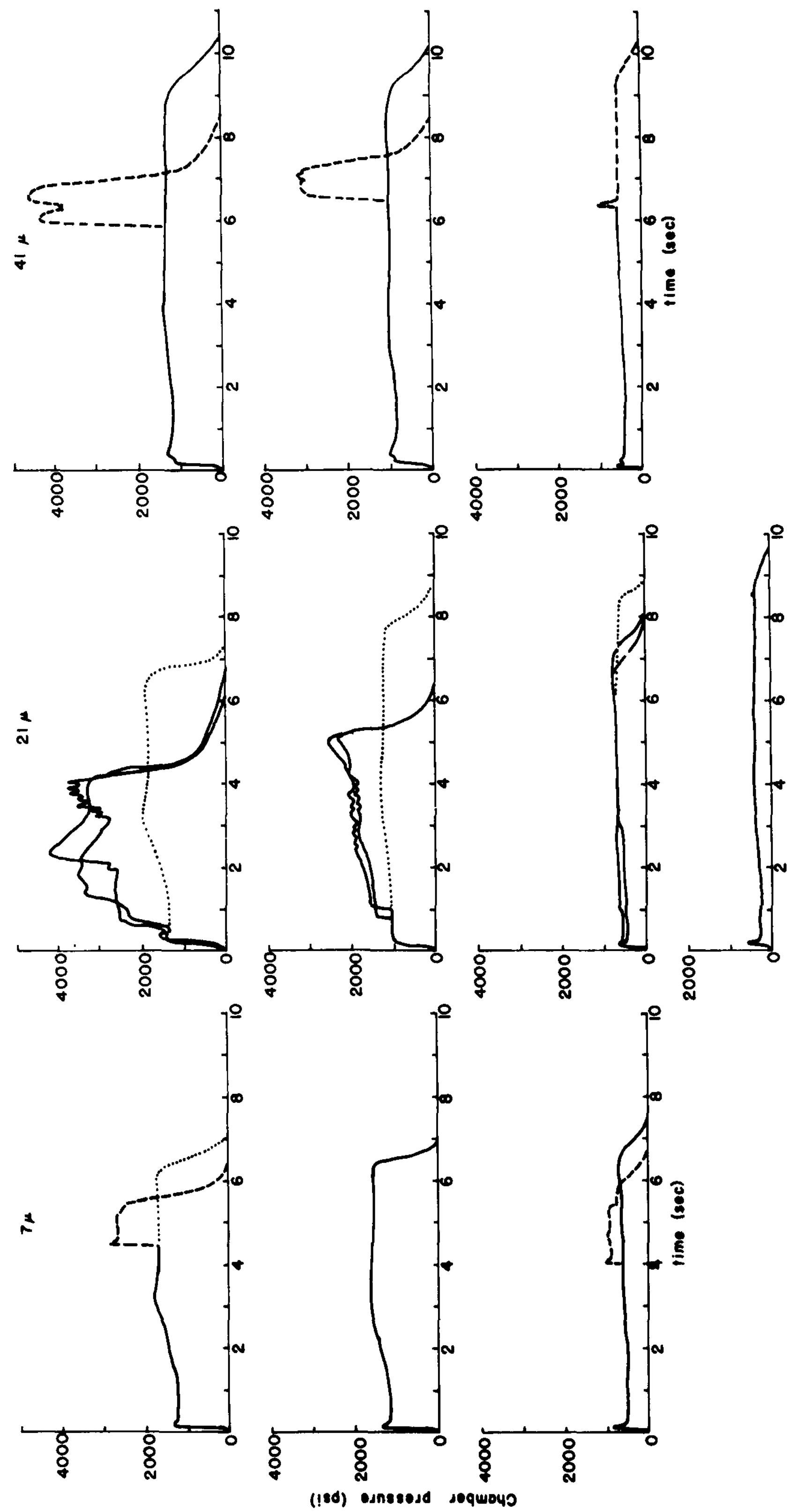


FIG. 9a. Summary of Pressure-Time Histories, Showing Effect of Aluminum Particle Size on Unstable Combustion of E-107 Propellant. Solid lines indicate behavior prior to pulsing. Dashed lines indicate history after application of pulse. Dotted lines show approximate pressure-time history for nonoscillating run.

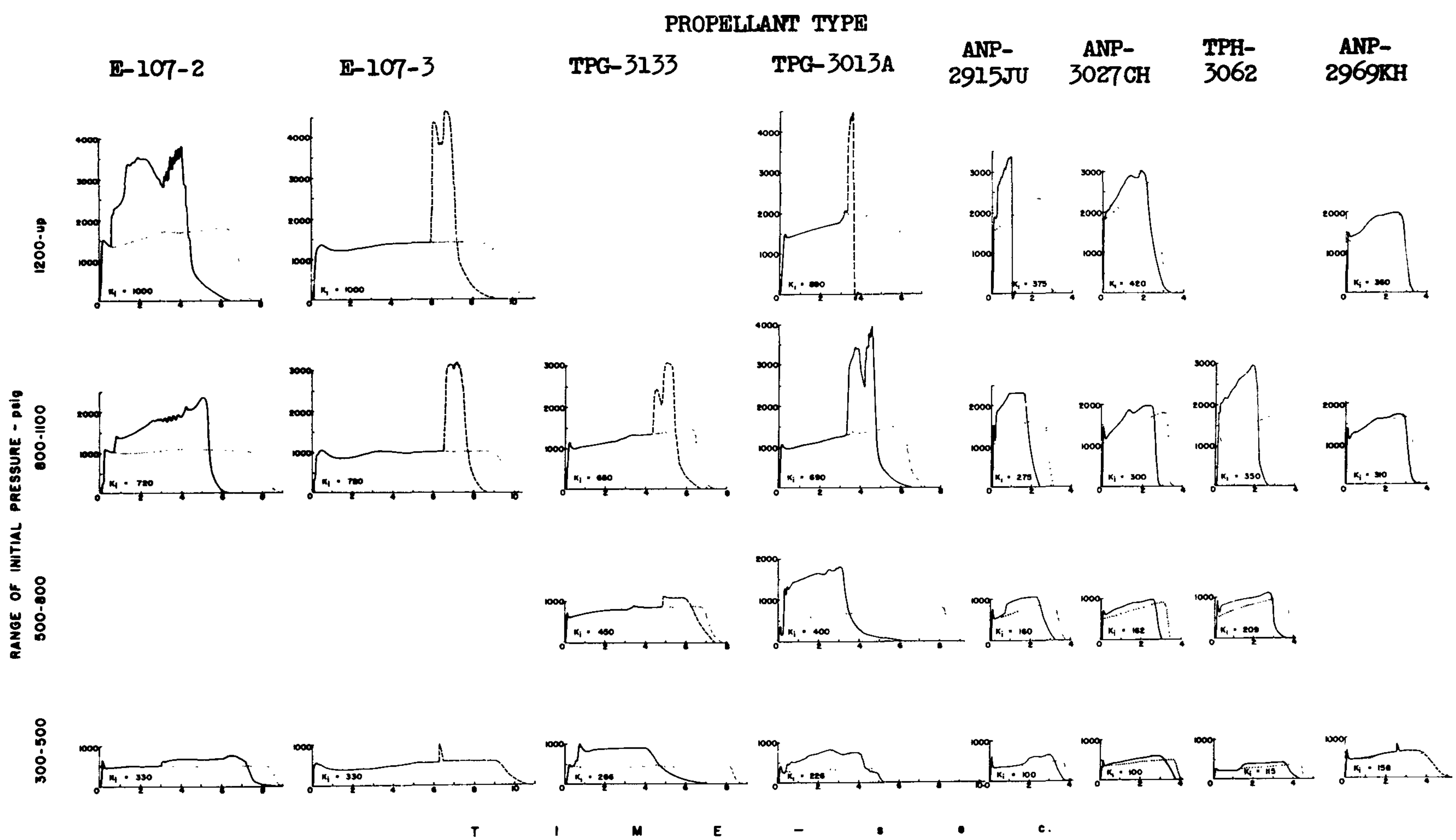


FIG. 9b. Summary of Pressure-Time Histories, Showing Effect of Compositional Variables on Unstable Combustion of Eight Propellants. Solid lines indicate behavior prior to pulsing. Dashed lines indicate history after application of pulse. Dotted lines show approximate pressure-time history from nonoscillating run.

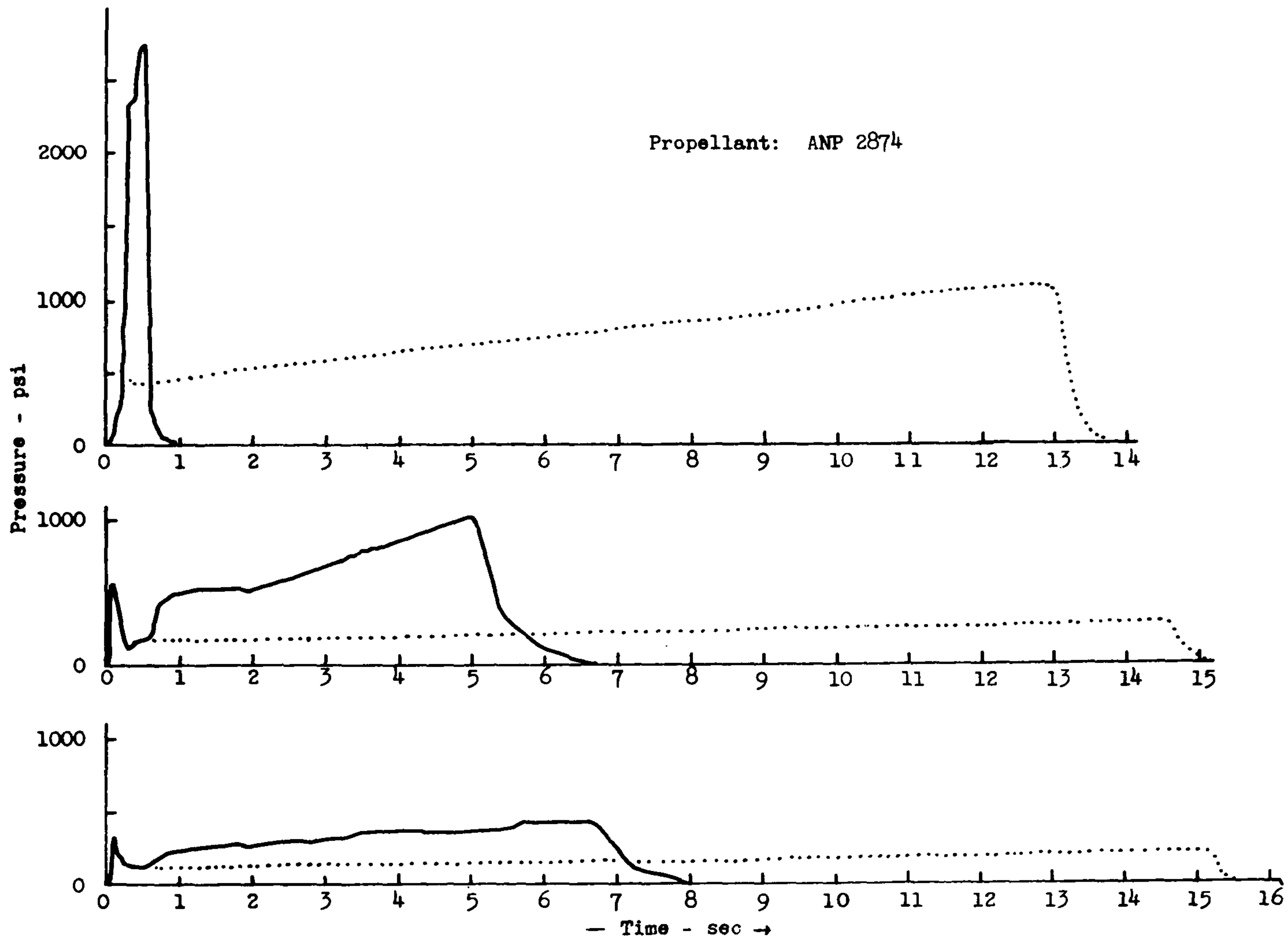


FIG. 9c. Summary of Pressure-Time Histories, Showing Behavior of ANP-2874HO Propellant. Solid lines indicate behavior prior to pulsing. Dashed lines indicate history after application of pulse. Dotted lines show approximate pressure-time history for nonoscillating run.

E-107 PROPELLANT

All preliminary work of this program was conducted using a polyurethane-ammonium perchlorate-aluminum propellant available at NOTS and designated E-107. In its usual form this propellant is relatively binder rich, uses a relatively coarse oxidizer, and uses aluminum powder which is considered to be typical or average particle size. In preliminary work the usual formulation of this propellant was used. However, extensive testing was made on three modified versions of this propellant, E-107-1, E-107-2, and E-107-3, in which special lots of powdered aluminum were used, providing mixes with three different particle sizes of aluminum with relatively narrow particle size distribution in each lot. Details of this propellant are shown in Table 1. All loadings were made at NOTS. The studies of the effect of aluminum particle size were funded primarily from a separate source and are being reported more fully in a separate report (Ref. 9).[2]

TPG-3133

This propellant is an ammonium perchlorate-polyurethane-aluminum type very similar to the one described in the last section but with partial replacement of the aluminum powder by a different grade with finer particle size. It was adopted in the SUBROC missile and has performed without combustion instability. Details of the composition and ingredients are shown in Table 1. Loading of these propellant charges was carried out by the Thiokol Chemical Corporation at no cost to the government.

TPG-3013A

This is an ammonium perchlorate-polyurethane-aluminum propellant used during the development of the SUBROC missile. It was of particular interest in this program because it exhibited severe axial-mode combustion instability at 180 cps in the SUBROC motor and had to be replaced by a modified version to obtain satisfactory motor performance. It is significant that this propellant is not greatly different from either E-107 propellant or from the propellant which ultimately replaced it (TPG-3133 described below). Details of the propellant are shown in Table 1. This propellant was supplied by the Thiokol Chemical Corporation under Contract No. N123(60530) 33583A.

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[2] Funded by the Bureau of Naval Weapons Special Projects Office under Task Assignment SP 19422.

ANP-2915 JU

This is an ammonium perchlorate-polyurethane-aluminum propellant utilized for the boost phase of the Improved Tartar missile. Axial-mode combustion instability was experienced with this propellant in the early configurations of this motor, sometimes in the form of mild sinusoidal oscillations and sometimes in the form of severe oscillations with elevated mean pressure. Such behavior has not been observed in the final configuration of the motor. This propellant has a lower binder content than the preceding propellants and a higher burning rate. Details of the ingredients and composition are shown in Table 1. Propellant loadings were provided by the Aerojet-General Corporation at no cost to the government.

ANP-3027 CH

This is an ammonium perchlorate-polyurethane-aluminum propellant similar to ANP-2915 JU, with a modified polyurethane binder and slight other differences in composition. In the Improved Tartar motor, ANP-3027 CH propellant consistently yielded mild axial-mode instability in the motor configuration that was stable with ANP-2915 JU. Details of the ingredients and composition are given in Table 1. Propellant loadings were carried out by the Aerojet-General Corporation under Contract No. N123(60530) 33331A.

TPH-3062

An ammonium perchlorate-carboxy terminated polybutadiene-aluminum propellant used in the Surveyor program, TPH-3062 was selected because it used a different binder than most of the other propellants in the program. No history of instability experience has been reported on this propellant. Details of the propellant are shown in Table 1. The loadings were provided by the Thiokol Chemical Corporation at no cost to the government.

ANP-2969 KH

This is an ammonium perchlorate-aluminum propellant with a nitro-polyurethane binder. It was chosen because of its high energy binder and because of extensive development experience with the propellant in the Polaris program. No history of instability experience has been reported on this propellant. Details of the propellant are shown in Table 1. The loadings were provided by the Aerojet-General Corporation at no cost to the government.

ANP-2874 HO

This is a polyurethane propellant with no aluminum and with an oxidizer blend consisting of ammonium perchlorate and nitroguanadine. It is a low burning-rate propellant used for the sustain phase of the Improved Tartar motor. This propellant yielded severe axial-mode instability with elevated mean pressure in several tests of an early configuration of the Improved Tartar motor. It has not exhibited instability in the present configuration. Details of ingredients are shown in Table 1. The propellant loadings were carried out by the Aerojet-General Corporation at no cost to the government.

EJC AND DDP-70

These are cast double-base propellants originally planned for this program because of extensive development experience with them in second stage Polaris. While separate funding was originally available for loading these propellants, negotiations for the loadings continued until expiration of the funding, so that no testing has been possible on this class of propellants to date. Loading hardware was constructed under Contract No. N(60530) 9635 with the Hercules Powder Company, and efforts are continuing to obtain loadings for future testing.

SUMMARY OF RESULTS BY PROPELLANT

A complete summary of test results is shown in Table 2 and Fig. 9. This summary does not include preliminary tests with standard E-107 propellant which were designed to evaluate the motor and charge design, igniter, and instrumentation techniques. The main test series reported here involved seven commercial propellants in addition to three variations of E-107 propellant. Tests were made over a range of pressures from 300 or 400 psi up to 1,500 psi or higher, with the particular pressures being chosen partly on the basis of the behavior exhibited and partly on the basis of the range of pressures in which the propellant had been used in development programs. In general, it was found that the test results were reproducible at any given test condition, with the result that a wide range of pressures could be tested with the small number of charges available. This was in contrast with the original intention of the program to test several charges at 1,000 psi, with tests at other pressures contemplated only in those instances where it was found that three tests at 1,000 psi were highly reproducible.

E-107-1, E-107-2, AND E-107-3

During the early phases of this program, a series of tests was made to permit standardization of hardware, instrumentation, ignition technique, etc. These tests used E-107 propellant, a standard mix available at NOTS. These tests are not reported here because they reflect factors of the evolving experimental approach not relevant to propellant comparison. Subsequent to these tests, 16 firings were made on three modifications of E-107 propellant using 7-, 21-, and 41-micron (μ) aluminum. Results are summarized in Fig. 9a. The effect of aluminum particle size was conspicuous; all tests with 21μ aluminum (E-107-2) developed mild and then severe form instability spontaneously, while tests with 7μ or 41μ aluminum (E-107-1 and E-107-3 respectively) showed only mild form instability unless pulsed. The low-pressure test with 41μ aluminum showed no instability, even when pulsed. Pressure rise during severe form instability was always large. Amplitude of oscillations was comparable to TPG-3013A and TPG-3133, less severe than ANP-2915 JU and ANP-2969 KH. Amplitude was greater at low mean pressure than high mean pressure. Frequency of mild form oscillations was low (250 cps) with 41μ aluminum, suggesting incomplete combustion of the aluminum; this interpretation was supported by the observation of normal frequencies (310 cps) during severe instability (when combustion rates are probably accelerated by acoustic stirring).

TPG-3133

Five firings were made on this propellant. Spontaneous mild form instability was evident in all tests, and severe form instability occurred spontaneously at low pressure. In medium and high pressure tests, only mild form instability occurred until the pulse charge was fired, but severe instability occurred after pulsing. Amplitude of the oscillations was comparable to that observed with the E-107 series, as was the pressure rise during oscillations. Severity of oscillations was greater at low pressure, as was the percentage pressure rise.

TPG-3013A

Six firings were made on this propellant. Spontaneous mild form instability was evident in all tests, and severe form instability occurred spontaneously in low and medium pressure tests. In the high pressure test, only mild form instability occurred until the pulse charge was fired; severe instability occurred after pulsing. Amplitude of the oscillations was appreciably greater than in the case of E-107 propellants or the companion propellant, TPG-3133, and the pressure rise during oscillation was correspondingly higher. This is consistent with the experience with TPG-3013A and TPG-3133 in the SUBROC program. In all respects stability was lower at low pressure than high--i.e.,

oscillations started more easily, went to higher amplitude with greater percentage perturbation of mean pressure in low pressure tests.

ANP-2915 JU

Five firings were made with this propellant. In all tests, mild form instability developed immediately after ignition. At high pressure the transition to severe form instability occurred spontaneously after a few cycles of oscillation, making the identification of the mild form from onset of the severe form doubtful. At low pressure, the transition was delayed and less precipitous. The severe form instability was very severe, with complicated "hashy" wave form. The pressure rise during severe form instability was around 60 percent, not very great considering the severity of the oscillatory behavior. Amplitude of oscillations was relatively pressure-independent.

ANP-3027 CH

Five firings were made with this propellant. In the high pressure tests, mild oscillations developed during the ignition transient, and progressed to severe form instability almost immediately. At lower pressures the mild form was erratic, gradually changing to severe oscillations. In all tests the amplitude of the severe oscillations was much less than in corresponding firings of the companion ANP-2915 JU propellant, with less "hashy" wave form; the rise in mean pressure due to oscillations was correspondingly low. Amplitude of pressure oscillations was relatively independent of mean pressure.

The relative stability of ANP-2915 JU and ANP-3027 CH observed in these tests is just the opposite of that in the Improved Tartar motor, where ANP-3027 CH consistently exhibited unstable behavior while ANP-2915 JU was stable in the same motor configuration. This observation can be reconciled if it is noted that the oscillatory behavior observed in the Improved Tartar motor exhibited a low amplitude, sinusoidal wave form much like the "mild form" instability in the present work. It is quite possible that the severity or prevalence of mild form instability in the present tests was greater for ANP-3027 CH, but no such judgment was made because of the observation of the mild form instability followed by severe form.

TPH-3062

Four firings were made with this propellant. All exhibited mild oscillations progressing continuously to severe oscillations. At high pressure the growth to severe oscillations was very rapid; at low pressure the mild oscillations increased in amplitude for the first 1.2

seconds, more rapidly at that time, and then continued with very large amplitude. The clear distinction between mild and severe form instability was less evident than with TPG-3013A, TPG-3133, and E-107. Behavior was much like ANP-2915 JU, except that wave forms of pressure oscillations were less complicated. Amplitude of pressure oscillations and accompanying pressure rise were both severe, about the same as for ANP-2915 JU.

ANP-2969 KH

Three firings were made with this propellant. All developed severe oscillations, preceded by periods of mild oscillations. At high pressure the mild oscillations were well defined but changed rapidly to severe oscillations. At medium pressure the mild oscillations were intermittent. At low pressure the mild oscillations progressed slowly to severe ones. The maximum amplitude was fairly high in every test, but not as high as with ANP-2915 JU or ANP-3062. The accompanying mean pressure rise was comparatively mild, less than with any other propellant tested.

ANP-2874 HO

Three firings were made with this propellant, all at low pressures in the range of the Improved Tartar sustainer operation. All tests started without sustained mild form instability. Growing sinusoidal oscillations started early, quickly became sharp-fronted, and grew to very large amplitude (considering low mean pressure of test). Pressure rise during instability is extremely large (several fold).

SUMMARY AND COMMENT

The original purpose of this investigation was to obtain an objective comparison of the instability characteristics of "commercial" propellants in the intermediate-frequency range, by testing them all in a single burner configuration. Propellants selected included some with prior instability history and some with no history of instability. It was not known in advance whether the previous pattern of instability and stability would be reproduced in these tests, because it was not known whether the history reflected primarily propellant combustion characteristics or acoustic characteristics of the various motors in which the propellants had been used. It was proposed to use a burner with relatively low acoustic losses, so that a reasonably stringent test of stability characteristics would be obtained. In the original plan, the limited objective of testing at 1,000 psi, 70°F, and 300 cps was

adopted for economic reasons. Because a second increment of funding was provided, and because reproducibility of tests was better than anticipated, it was possible to test over a wide pressure range. In addition, the second increment of funding made it possible to adopt pulse testing, which was used in most firings where instability did not occur spontaneously.

The initial question posed in this work is answered decisively by the test results; all of the propellants tested were unstable in the low-loss burner, so that stability in rocket motors is evidently contingent on high acoustic losses (at least with acoustic-mode frequencies in the vicinity of 300 cps). The propellants differ significantly with respect to stability characteristics, but the behavior is too complex for a single simple stability ranking. In particular, there appear to be at least two modes of instability (referred to here as "mild form" and "severe form"), with one mode exhibiting nonlinear initiation characteristics. There is no evidence that the ranking of the propellants with respect to one of these two forms of behavior would be the same as ranking relative to another form. In addition, the severity of the oscillatory behavior and the deviation of the propellant burning rate from normal during oscillations are both of practical interest, and ranking relative to these attributes would also apparently not lead to the same ordering of the propellants. While the tests here were too limited to establish quantitative ranking relative to the attributes noted, a qualitative summary is presented in Table 3.

There are several generalizations that are of practical importance that seem justified on the basis of the results of the present and related work at NOTS.

1. The absence of instability in a development program provides no basis for confidence in stability characteristics of the propellant. All propellants tested were unstable, and severely unstable propellants were in some cases stable in the development program (e.g., ANP-2969 KH and TPH-3062).

2. The particle size of the powdered aluminum plays a dramatic role in the combustion instability, especially the severe form.

3. Instability is not uniquely dependent on the binder, as it was common to all three binders involved in the program.

4. Some of the propellants did not burn unstably until triggered by a finite flow disturbance--suggesting the importance of designing motors to avoid disturbances. (It is possible that this nonlinear initiation is characteristic of all the propellants tested, but the losses in the burner were so low that most of the propellants started oscillatory combustion before pulsing could be carried out to resolve this point.)

5. Stability characteristics were quite pressure-dependent with some propellants--but no generalization can be made because trends were not the same with all propellants nor for all aspects of instability (e.g., TPG-3013A and TPG-3133 were less stable at low pressure while E-107-3 was more stable at low pressure).

6. In addition to dependence of the instability on mean pressure as reflected in the present burner tests, there is a tendency towards increased stability at low pressure in rocket motors because of associated large nozzle throat area and high acoustic losses at low pressure. A similar tendency towards increased stability with high burning-rate propellants is expected in rocket motors for the same reason--large nozzle throat area. These are not attributes of the combustion, but rather of the motor configuration, and are largely absent in the center-vented burner tests.

7. Combustion behavior of propellants containing powdered aluminum has been found to be frequency-dependent in the range below 500 cps (Ref. 10), so that comparisons based on a test series (such as the present one) at constant frequency should not be applied recklessly to systems with different acoustic mode frequencies. Further studies of frequency dependence are needed to assess the seriousness of this problem.

TABLE 3. Comparison of Stability Characteristics of Several Propellants at 70°F and 300 cps

Stability characteristics / Propellant	Mild form	Severe form	Burning rate deviation during severe form[a]
E-107-1	Medium severity, all pressures	Medium at all pressures; occurred only when pulsed	High
E-107-2	Medium severity, all pressures	Occurred spontaneously all tests; medium; onset delayed at low pressure	High
E-107-3	Medium to low, absent at low pressure	Occurred only when pulsed; medium; at low pressures did not occur when pulsed	High
TPG-3133	Medium to high, higher at low pressure	Medium at all pressures; at high and medium pressures occurred only when pulsed	High
TPG-3013A	Medium	Medium to severe at all pressures; occurred at high pressures only when pulsed	High
ANP-3915JU	Medium severity, all pressures, progressive and hence not completely distinct from severe form	Severe at all pressures; occurred spontaneously early in test	Medium; high at low pressure
ANP-3027CH	Low and erratic, progressive and hence not distinct from severe form	Medium and spontaneous at all pressures, erratic early in test	Medium
TPH-3062	Medium, but progressive to severe form, hence not distinct from severe form	Severe and spontaneous at all pressures, initiates early in tests, retarded at low pressure	Medium to low
ANP-2969KH	Medium, not too distinct from severe form	Medium to severe at all pressures, occurred spontaneously	Low
ANP-2874HO	Not evident as distinct from start of severe form	Severe at the low pressures tested, occurred spontaneously early in test	Very high

[a] Evaluation made with allowance for the severity of the oscillatory behavior causing the burning rate deviation. Rating is based on deviation of pressure from normal.

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